SIMPLE, FULLY FEATURED BOILER LOOP MODELLING

Erica Kenna[1], and Paul Bannister[1]
[1]Exergy Australia Pty Ltd, PO Box 546, Belconnen ACT 2616 Australia
Paul@xgl.com.au

ABSTRACT

The performance of hot water space heating systems for mild to warm temperate climates is dominated by the efficiency of boiler operation at low load (i.e. below 25% of nameplate capacity). This efficiency is influenced by a number of effects that are poorly represented in common modelling approaches, including static thermal losses from the boiler and distribution system, changes in burner efficiency at different firing rates, thermal inertia in the boiler loop and the effects of cyclic operation.

In this paper, a simple model that includes these loss mechanisms is developed. An example from an actual project is used to demonstrate that addressing the full range of low-load efficiency effects can increase predicted boiler gas consumption substantially relative to standard simulation approaches.

INTRODUCTION

In mild to warm temperate climates such as experienced in coastal centres in temperate Australia and much of the west coast of the US, boiler operation is dominated by operation at low load. In Australia at least the impacts of this are often increased by the use of poorly designed boiler plant. When challenged at design stage, simulation is often used to justify design decisions. However, the energy use predicted is often extremely low (typically below 10MJ/m^2), which is well below the levels achieved for actual boiler consumption post-construction, even when tuned and commissioned to best practice. This calls into question the appropriateness of common boiler simulation methods for this climatic region.

In this paper, a simplified model of boiler operation is presented that takes into account the major factors that affect efficiency at part load. It is demonstrated that this model calculates significantly higher fuel consumption estimates than incumbent methodologies.

There is a variety of different ways in which simulations address the modelling of boilers. The main methods appear to be the use of a model internal to the simulation program, such as is examined for DOE-2.1e in this paper, the use of a simple boiler fuel input to load table, or the assumption of a constant efficiency level.

It is generally recognised (e.g. CIBSE 2004) that boiler performance shows a plateau of near-peak efficiency down to around 25% part load and then decays rapidly as the load decreases further. This means that boilers operating for long periods at low load may operate at poor efficiency. The representation of this effect is critical to obtaining realistic estimates of boiler consumption and to the assessment of boiler sizing and staging issues.

The DOE-2.1e computer simulation program (LBL 1982, Winkelmann et al 1993) includes a template-type representation of boiler and heating water systems. The boiler model makes use of user-specified polynomial functions to describe the boiler performance. While in theory this provides a method for describing many features of boiler performance it is reliant upon both the suitability of the available model parameters and the availability of reasonable measured data against which to fit performance curves. Unfortunately, such data appears extremely difficult to obtain, even for new boilers. As a result, simulators have to rely on defaults or make best-guess estimates. However the ability to make estimates is compromised by the lack of physical meaning in the curve fit parameters. Thus, a simulator cannot use known information about a model to make a reasonable estimate of its likely efficiency curve without generating an entire model of boiler operation. Furthermore, it is impossible to represent a range of common controls features, such as lock-out temperatures and heating calls, and the representation of hot water loop thermal inertia is absent. As a result, a model of the nature used in DOE2.1e provides only limited benefit over other estimation methods. Similar limitations appear to affect most other simulation packages in commercial use.

In response to these problems, we have created a simple methodology for representation of boiler and heating loop performance based on estimable or obtainable physical parameters, suitable for spreadsheet implementation. This can then be used as a post-processor for simulation-generated boiler loads. Although the model is based on fully modulating gas-fired low temperature hot water boilers it is adaptable to other boiler types.

METHOD

Inputs to the model

The inputs to the spreadsheet model comprise a number of design parameters and estimates or assumptions about how the heating system will run. These are:

- The average hourly heating loads passed on by the heating coils to the plant. Hourly heating loads for the coils are reported by the simulation package using its customizable hourly reporting feature.
- Boiler output capacity.
- Minimum output capacity at which the boiler can continuously operate.
- Burner combustion efficiency.
- Mass of water in the heating water distribution system.
- A "base load", representing losses in the heating water distribution system that are imposed on the boiler whenever it is enabled.
- A "cut-out ambient temperature", above which the system will not operate. This reflects the use of a boiler lockout control.
- Design operating temperature of water in the distribution system. For this simple model, we have assumed that the temperature throughout the distribution system is uniform.
- Nominal operating period for the burner during cyclic operation.
- Minimum interval between cycles during which the burner will not restart.
- Standing losses of the boiler, which are assumed to be constant during any hour that the boiler operates.
- Purge losses associated with burner ignition.
- Ambient temperature of areas surrounding the distribution system (i.e. plant rooms and risers). For this simplistic model a constant temperature was assumed.

Appropriate values for many of these items can readily be determined from the mechanical specification or sourced from boiler manufacturer.

Combustion efficiency

The combustion efficiency is the efficiency at which the fuel is converted to heat inside the boiler, without consideration of the heat transfer to the heat transfer fluid.

The losses affecting the combustion efficiency are the intake air and gas enthalpy, the flue gaseous thermal losses, flue solids thermal losses and incomplete combustion. In practice, only the flue gaseous losses are significant for gas fired boilers.

In practice, the flue losses are a function of the stack temperature and the excess air ratio, where the latter is the amount of air beyond that required to provide complete combustions in theory. Typically, stack temperatures range from 200-220°C when the burner is at 100% to 140-150°C when the burner is at low flame (25%) (ASHRAE 2000).

The excess air quantity is ideally maintained at a constant percentage, under which circumstances the combustion efficiency rises as the burner flame reduces. In practice however, excess air management is problematic due to the difficulty in effectively regulating airflow. Constant excess air flow is only really achievable with excess air control modulated direct by the measured oxygen level in the boiler flue also known as "linkageless control". This contrasts with the more common method of using a direct mechanical linkage from the burner control to the air control, which tends to cause excess air to increase as the burner flame reduces (Carpenter et al., 2008).

Typical curves are shown in Figure 1 below. These can be readily represented as linear functions of boiler input power.

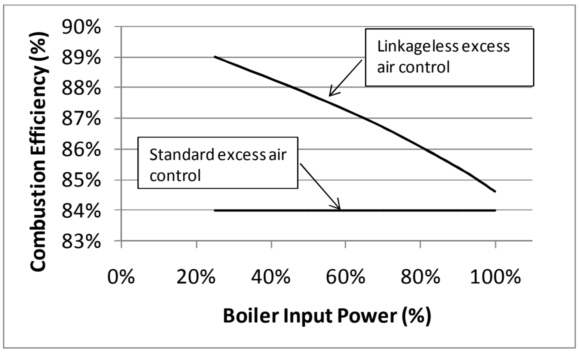

Figure 1. Typical combustion efficiency curves. The upper curve is taken from ASHRAE 2000.

Determining the boiler loop load

For each hour, the distribution system load Q_{loop} on the boiler is determined as follows:

$$Q_{loop} = Q_{coil} + Q_{base} + Q_{dynamic}$$

The heating coil load Q_{coil} is input from the simulation. The heating system conductive and convective losses Q_{base} is typically estimated based on available design information. The "dynamic load" $Q_{dynamic}$ is the heat input associated with the change in temperature of the thermal mass of water and metal within the heating distribution system and boiler, a term which can be significant when a boiler operates from a cold start.

Calculating the dynamic load

To calculate the dynamic load, it is firstly necessary to determine the temperature of the fluid in the heating water distribution system when boiler operation commences. The spreadsheet model does this by tracking the temperature in the distribution system on an hourly basis. When the boiler is not running, the temperature decays exponentially from its design value to match the ambient value assumed for plant rooms and risers. An example is illustrated in Figure 2.

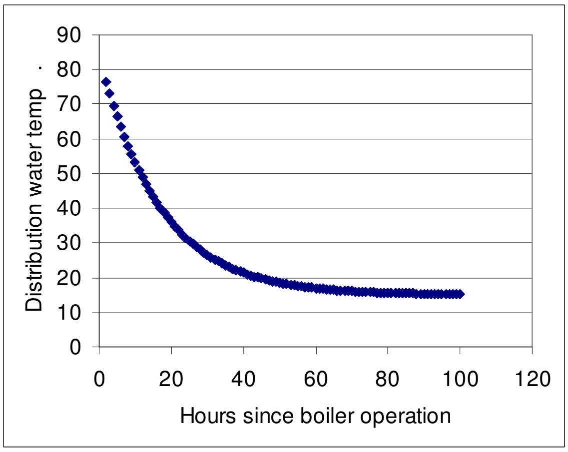

Figure 2: Temperature in the heating fluid distribution system.

The temperature curve illustrated in Figure 2 is calculated as follows:

$$T_h = T_{h-1} - \frac{Q_{h-1}}{mc_p}$$

where

- T_h is the temperature in the current hour (°C); and
- T_{h-1} is temperature during the previous hour (°C);
- Q_{h-1} is the heat lost from the system during the previous hour (kJ);
- m is the mass of water in the system (kg)
- and c_p is the specific heat of the fluid in the distribution system (kJ/kgK).

Heat lost from the distribution system is calculated as:

$$Q_{h-1} = Q_{base}^{designT} \frac{T_{h-1} - T_{amb}}{T_{design} - T_{amb}}$$

where

- $Q_{base}^{designT}$ is the assumed base load, when the working fluid is at design temperature, associated with losses in the distribution system (kJ).
- T_{design} is the average design operating temperature of the fluid in the distribution system when the boiler is enabled (°C);
- and T_{amb} is the ambient temperature in the plant rooms and risers (°C).

An example of the heat transfer rate determined from these equations is illustrated in Figure 3:

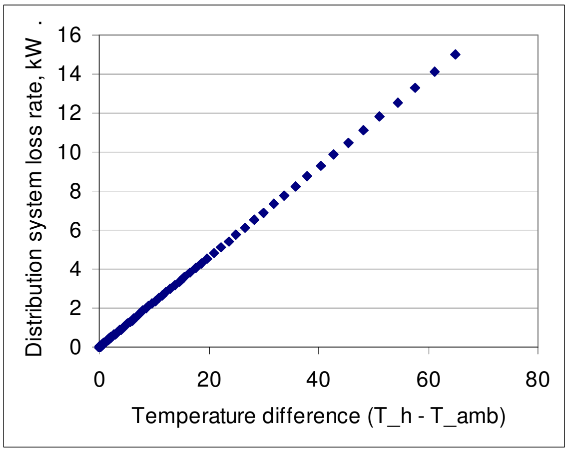

Figure 3: Distribution system heat loss rate as a function of the temperature difference between heating water and ambient.

The key assumption underlying these calculations is that the main mechanisms for heat transfer from the boiler loop to its surroundings are conductive and convective.

Once the temperature in the distribution system is known, the dynamic load during any hour where the boiler starts can be calculated as:

$$Q_{dynamic} = mc_p(T_{design} - T_{h-1})$$

Determining the boiler operating profile

Once the boiler loop load is determined, the number of boilers required to meet this load can be calculated by comparing the system load with the boiler capacity. If more than one boiler is required, the load is assumed to be distributed evenly across multiple boilers.

If the average load on each boiler is below its minimum continuous operating point, the number of burner cycles per hour is determined using the formula:

$$N_{cycles} = \frac{Q_{loop} + Q_{cr}}{t_{burn}\dot{Q}_{min} - Q_{purge}}$$

where:

- N_{cycles} is the number of cycles per hour;
- Q_{cr} is the boiler convection and radiation loss in one hour (kJ)
- t_{burn} is the minimum burn time;
- $\dot{Q}_{min}$ is the minimum continuous operating power for the boiler; and
- Q_{purge} is the burner purge loss, per purge cycle.

A lower load results in fewer cycles - that is, longer intervals between burns. The burn time during cyclic operation is assumed to be constant, regardless of the load.

If the average load on the boiler is above the minimum continuous operating point the boiler is assumed to run continuously.

Determining the boiler fuel consumption

For hours where the boiler runs continuously the boiler losses are simply the standing losses, so the boiler fuel consumption Q_f per hour:

$$Q_f = \frac{Q_{loop} + N_{boilers} Q_{cr}}{\eta_{comb}}$$

where η_{comb} is the boiler combustion efficiency. If the boiler cycles on and off then the purge losses also need to be considered in calculating the total boiler losses, so the equation becomes:

$$Q_f = \frac{Q_{loop} + N_{boilers} Q_{cr} + N_{cycles} Q_{purge}}{\eta_{comb}}$$

Optional Extras

A number of extras can be incorporated into the model if required:

- Hot water distribution pumping energy can readily be estimated in the spreadsheet based on modelled pump operating hours and design motor sizing. Some additional complexity is added if a variable flow or primary/secondary arrangement is in use but this is relatively uncommon for boilers.
- Electrical energy associated with burner fans, controls, and other boiler auxiliaries can be incorporated.
- A “cut-out load” below which the system would not operate could be used to represent the affect of a “heating-call” type control.
- Intermediate distribution loop operating temperatures and losses may need to be considered on start up if the boiler size is insufficient to meet total system loads.
- Blow-down losses would need to be added for steam boiler installations.

How does the model compare with DOE 2.1e?

DOE 2.1e uses a template-type representation of the boiler which allows the user to input:

- Capacity
- Boiler type (hot water or steam)
- Minimum turndown ratio for continuous operation
- Heat Input Ratio (H_{des}), which defines the full load efficiency of the boiler, i.e. it is the ratio of fuel in to heat out when the boiler is running at full load.
- Default equipment polynomial curve parameters were used. The equipment curves define the efficiency of the boiler at reduced part load.

The energy consumption at part load is calculated in the simulation engine as:

$$Q_f = C H_{des} H(x)$$

where C is the boiler capacity, H_{des} is the ratio of fuel input to heat output at full load and $H(x)$ is a function ranging from 0 to 1 describing the ratio of part load heat input to full load heat input x calculated using the equipment polynomial, of typically 2nd order:

$$H(x) = a + bx + cx^2$$

The parameters a, b and c are able to be specified in DOE-2.1e. DOE-2.1e also assumes that the boiler efficiency below the minimum capacity is constant, fixed at the efficiency H(x) evaluated at the minimum turndown ratio.

RESULTS

We ran the model described to represent an installation comprising two identical 900 kW boilers serving a 15,000 m² office building in Sydney. The boiler serves primary heating coils only, on several major air handling units with some 24/7 operation.

We constructed a dynamic computer simulation of the building using DOE-2.1e to generate the hourly heating coil loads for input to the model. The simulated building form, envelope, internal loads, air handling systems were defined in the simulation package following the guidelines of the *ABGR Computer Validation Protocol for Simulations (DEUS 2006a).*

Basic design and operating parameters of the installation were then input to the boiler spreadsheet model as listed in Table 1. DOE 2.1e boiler parameters used for comparison purposes are listed in Table 2. The resultant part load efficiency curves, for the two models are shown in Figure 4. It can be seen that the DOE 2.1e model has an unrealistic “flat” efficiency below the minimum turndown ratio.

Annual gas consumption figures for the simulation and spreadsheet model are compared in Table 3. It can be seen that the DOE 2.1e model predicts a significantly higher average efficiency and consequently less gas consumption.

In Figure 5 it can be seen that the differences in predicted consumption are greatest in periods of low load, as would be expected, although the absolute gas consumption difference is dominated by shoulder season consumption.

In Figure 6 it can be seen that the predicted efficiency in summer months is extremely low, reflecting the important of the dynamic losses in determining the overall system efficiency.

Table 1
Boiler parameters, example spreadsheet model

ITEM	VALUE	SOURCE
Boiler output capacity	900 kW /boiler	Mech. Spec.
Number of boilers	2	Mech. spec.
Minimum continuous operating point	225 kW_{out}	Boiler/burner supplier. 25% is typical for a modulating burner.
Burner combustion efficiency	83%	Nominal value from boiler supplier.
Mass of water in distribution system	3700 kg	Mech. spec.
Distribution system "base load"	15 kW	Assumed value for a relatively small, well insulated distribution system.
Distribution system "cut out temperature"	18°C	Assumed.
Design distribution operating temp	80°C	Mech. spec. Intermediate between flow and return temperatures.
Nominal burner cycle length	5 minutes	Assumed.
Minimum interval between burner restarts	1 minute	Assumed.
Standing losses of the boiler	27 kW	Assumed (3% is typical).
Ignition purge losses	0.18 kWh/cycle.	Estimated from burner airflow rate and assumed chamber temp of 100°C.
Plant room/riser ambient temperature	15°C	Assumption based on building location and construction type.

Table 2
DOE 2.1 plant parameters

ITEM	VALUE
Capacity	900 kW
Type	Hot-water
Minimum turndown ratio	25%
H_{des}	125%
Equipment-quad curve	DOE 2.1e defaults for hot water boiler, i.e. a = 0.082597, b = 0.996764, c = -0.079361

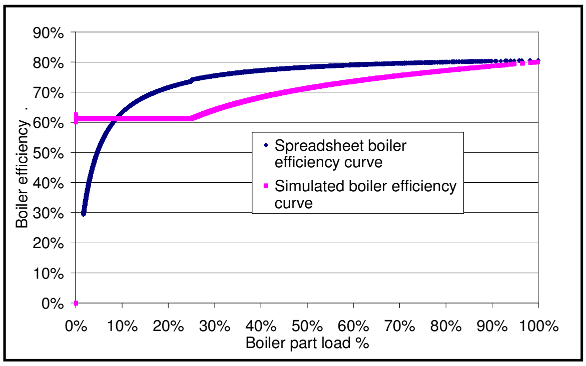

Figure 4: Boiler efficiency in the simulation and the spreadsheet

Table 3
Comparison of spreadsheet and simulation results

ITEM	SIMULATION	SPREADSHEET
Heating coil loads, GJ	1,050	1,050
Annual gas consumption, GJ	1,628	2,213
Seasonal efficiency (coil loads/gas consumption)	64%	47%

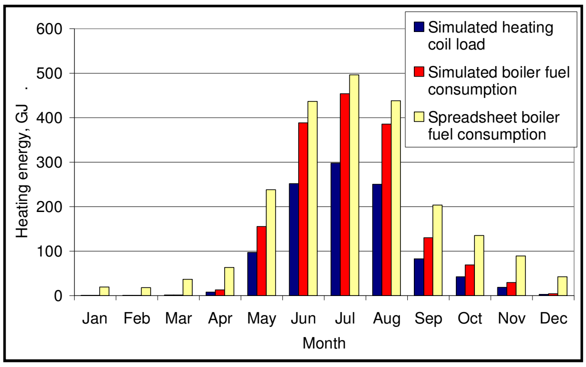

Figure 5: Comparison of simulation and spreadsheet fuel consumption.

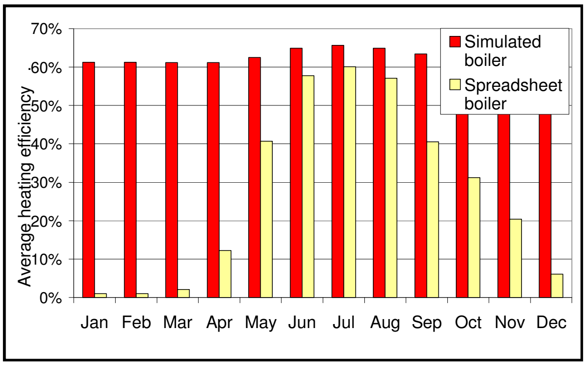

Figure 6: Comparison of simulation and spreadsheet efficiency

The total difference in energy consumption is significant in the mild Sydney climate, particularly outside the winter period. This is due to the dominance of low and transient loads, where DOE-2.1e assumes that the boiler efficiency will remain equal to its minimum continuous operating point, but where the spreadsheet allows dynamic loads and cyclic operation to be represented. These factors will also be significant in colder regions, if the boilers are significantly oversized - as is common practice. Not shown in Table 3 are the results for the commonly assumed constant boiler efficiency, which would be typically chosen at 75-80%. The predicted gas consumption for such a model would be 40% lower than that predicted by the spreadsheet.

While it is arguable that the DOE 2.1e model could be further fine tuned, the lack of available empirical data means that the basis for doing so is weak in the absence of a model using assessable physical parameters of the type presented in this paper. Furthermore, the dynamic load effects represented in the spreadsheet model would remain unrepresented.

CONCLUSIONS

A simple model representing boiler performance using physical parameters has been developed. The purpose of this model is to provide a simple methodology for representing boiler performance in a manner that is more justifiable than common estimation methods and more readily controlled and understood than internal boiler models for simulation packages such as DOE 2.1e.

The model explicitly represents real physical parameters such as boiler and distribution system standing losses, thermal mass of the fluid in the distribution system, and purge losses during cyclic operation. It is easy to set minimum operating temperature or load conditions to represent a boiler lockout or heating call. These features are important in the warm Australian climate, where low and transient loads can be dominant.

The model has been developed and implemented in a spreadsheet format, enabling it to be used as a post-processor for simulation-generated boiler loads. Within such a platform, it is also easy to incorporate a number of other control features that are not available in simulation packages.

The methodology has been laid out in this paper with the intent that other simulators adapt and use this model where appropriate to improve the accuracy of boiler fuel use estimation.

Acknowledgements

The assistance of Hongsen Zhang in reviewing boiler combustion efficiency in detail is acknowledged.

REFERENCES

ASHRAE Systems and Equipment Handbook SI Edition, 2000 Figure 7 page 27.6.

Carpenter, K., Schmidt, C., Kissock, K. Common Boiler Excess Air Trends and Strategies to Optimise Efficiency, Proceedings, American Council for an Energy Efficient Economy Summer Workshop, pages 3.52-3.63.

CIBSE (Chartered Institution of Building Services Engineers), Energy Efficiency in Buildings – CIBSE Guide F, 2nd ed. London January 2004. Refer to Section 10 for discussion of boiler efficiency issues.

DEUS (Department of Energy Utilities and Sustainability), 2006. For information on the National Australian Built Environment Rating System in general and associated documentation, refer to www.nabers.com.au.

DEUS (Department of Energy Utilities and Sustainability), 2006. *ABGR Validation Protocol for Computer Simulations.* Available from www.abgr.com.au.

LBL (Lawrence Berkeley Laboratory Energy and Environment Division, Building Energy Simulation Group and Group Q-11, Solar Energy Group, Energy Division, Los Alamos National Laboratory). *DOE-2 Engineers Manual V2.1A*, Lawrence Berkeley Laboratory Report LBL-11353 November 1982.

Winkelmann, F.C, Birdsall, B.E., Buhl, W.F, Ellington, K.L., Erdem, A.E., Hirsh J.J., Gates, S. 1993. *DOE-2 BDL Summary Version 2.1E.* Lawrence Berkeley Laboratory Report LBL 34946 November 1993.